

Evaluation of seismic design spectrum based on UHS implementing fourth-generation seismic hazard maps of Canada

Ali Ahmed¹  · Rafiq Hasan² · Oscar A. Pekau³

Received: 14 March 2016 / Accepted: 22 October 2016 / Published online: 7 November 2016
© The Author(s) 2016. This article is published with open access at Springerlink.com

Abstract Two recent developments have come into the forefront with reference to updating the seismic design provisions for codes: (1) publication of new seismic hazard maps for Canada by the Geological Survey of Canada, and (2) emergence of the concept of new spectral format out-dating the conventional standardized spectral format. The fourth-generation seismic hazard maps are based on enriched seismic data, enhanced knowledge of regional seismicity and improved seismic hazard modeling techniques. Therefore, the new maps are more accurate and need to incorporate into the Canadian Highway Bridge Design Code (CHBDC) for its next edition similar to its building counterpart National Building Code of Canada (NBCC). In fact, the code writers expressed similar intentions with comments in the commentary of CHBCD 2006. During the process of updating codes, NBCC, and AASHTO Guide Specifications for LRFD Seismic Bridge Design, American Association of State Highway and Transportation Officials, Washington (2009) lowered the probability level from 10 to 2% and 10 to 5%, respectively. This study has brought five sets of hazard maps corresponding to 2%, 5% and 10% probability of exceedance in 50 years developed by the

GSC under investigation. To have a sound statistical inference, 389 Canadian cities are selected. This study shows the implications of the changes of new hazard maps on the design process (i.e., extent of magnification or reduction of the design forces).

Keywords Uniform Hazard Spectrum · Probability of exceedance · Seismic response coefficient · Confidence level

Introduction

Introduced by Biot (1933, 1934) and Housner (1941, 1947), the response spectrum has become an essential tool to analysis and design of structures in seismic regions. The construction of design spectrum uses a conventional standardized shape based on a single control point as shown by ordinate y_0 at period $T = 0$ in Fig. 1a derived from site-specific ground motion parameters for a specific probability level and damping. This approach is seen to be consistent and conservative with respect to the well-known parameters pseudo-acceleration A , pseudo-velocity V and relative displacement D with the relations among them

$$A = \frac{2\pi}{T} V = \left(\frac{2\pi}{T} \right)^2 D \quad (1)$$

i.e., pseudo-acceleration declines at a rate proportional to $1/T$ and $1/T^2$ for the constant velocity and displacement zones, respectively.

Although this procedure for design spectra had been widely used for several decades in bridge and building design codes, it has long been recognized that the method involves a considerable discrepancy in getting spectral ordinates of other periods derived indirectly from the single

✉ Ali Ahmed
aliahmed@stamforduniversity.edu.bd
Rafiq Hasan
hasan_rf@yahoo.ca
Oscar A. Pekau
oscar.pekau@concordia.ca

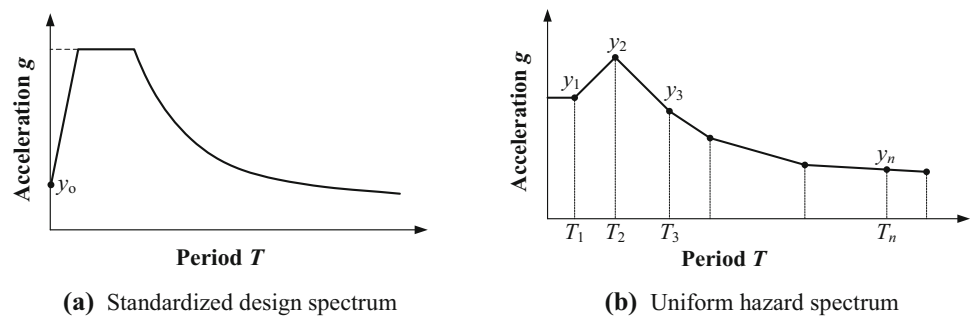
¹ Department of Civil Engineering, Stamford University
Bangladesh, Dhaka 1217, Bangladesh

² 408-70 Absolute Avenue, Mississauga, ON, Canada

³ Department of Building, Civil & Environmental Engineering,
Concordia University, Montréal, Canada



Fig. 1 Design spectra using single and multiple control points



control point. Alternatively, Uniform Hazard Spectrum (UHS) in which a design spectrum is constructed by connecting multiple site-specific control points $y_1, y_2, y_3, \dots, y_n$ corresponding to $T_1, T_2, T_3, \dots, T_n$ as shown in Fig. 1b has been emerged. These control points are obtained from the spectral amplitudes that have a specific probability associated with a specific level of confidence for a reference site and damping. Therefore, the UHS eliminates the need of predefined spectral shape and may not resemble the so-called standard spectral shape. Since the resulting spectrum is drawn based on multiple site-specific control points, it provides more accurate design force, and better hazard assessment. It also offers more uniform level of safety across the geographical regions of applicability by having the hazard maps on the basis of lower probability level. In recent times to facilitate the implementation of UHS in design codes, probabilistic seismic hazard maps have been developed by the Geological Survey of Canada (GSC) and the United States Geological Survey (USGS). These maps portrayed ground motion values [peak ground acceleration PGA and spectral amplitudes $S_a(T)$] at $n\%$ probability of exceedance in Y years ($n\%$ in Y -year) for 5% damped SDOF systems at reference site. With the availability of new hazard maps (e.g., fourth-generation seismic hazard maps of GSC), design codes in the USA and Canada implemented UHS and have provided construction procedures of spectrum using the control points for the whole practical range of periods and laid out the detail guidelines of application (e.g., NBCC 2005; AASHTO 2009). It is interesting to note that the probability level of the hazard maps for NBCC moved from as high as 50% to as low as 2% (Hasan et al. 2010).

The issue of lowering probability has got much attention in recent times in the USA and Canada (e.g., BSSC 1997; Adams et al. 1999 etc.). Studies had pointed that lowering the probability level from 10% in 50-year (widely used in recent codes) provides a better basis for a uniform level of safety across the geographic boundary of applicability of the codes in Canada and the USA and is consistent with the expected target performance of structures. For example, analysis results indicate that buildings designed according to NBCC 1995 (i.e., for a 10% in 50-year design force

level) have actually strengths close to the 2% in 50-year design force level in terms of building drifts (Heidebrecht 1999; Biddah 1998). It was also shown that the use of 10% in 50-year hazard as the design basis results in significantly dissimilar risks of structural failure in different regions of Canada. As the design basis probability level, 2% in 50-year probability level was recommended for NBCC revision. A similar reasoning presumably has pushed AASHTO guide specification (AASHTO 2009) to adopt a lower probability level of 5% in 50-year.

Until the beginning of current millennium, two prominent codes (Ontario Highway Bridge Design Code OHBDC and Design of Highway Bridges—A National Standard of Canada, CAN/CSA-S6) were in effect to regulate bridge design practices in Canada. Likewise, previous NBCC (1995) and current CHBDC (2006) use a standardized spectrum with 10% in 50-year probability hazard maps. However, CHBDC differs in several ways from its building counterpart with reference to seismic force calculation and detail issues involved with analysis, e.g., (1) treatment of inherent material over-strength (CHBDC does not use calibration factor U), (2) treatment of higher mode effects (CHBDC does not use top floor force F_t and moment reduction factor J), etc. For this study, NBCC seismic provisions not relevant to bridge applications will be kept beyond the purview.

As NBCC and AASHTO in their recent revisions have adopted UHS with low probability of hazard maps, it is inevitable that Canadian bridge design community will take a similar pursuit. Then, inquiry is necessary for these developments to check if: (1) UHS a better spectral shape for CHBDC; and (2) hazard maps are used with low probability level. If low probability level is possible, then what the level is. On such backdrop, a general concern existing among the practicing engineers is that a lower probability may translate a higher seismic design force and eventually higher construction cost. These issues are addressed in this study. Thus, elastic seismic response coefficient C_{sm} are evaluated as defined in CHBDC for 389 Canadian cities. But the results of sixteen major Canadian cities are presented for brevity. It compares the C_{sm} values with those of current CHBDC, tracks the magnification and



reduction of C_{sm} for a set of periods and investigates the best probability level for CHBDC using site-specific UHS.

Ground motion probability level

In Canada, the Geological Survey of Canada (GSC) publishes seismic hazard maps periodically matching the need of time. In recent years, the GSC developed a new set of hazard maps/data (Adams and Halchuk 2003). This set of maps is called fourth-generation seismic hazard maps for Canada. The maps consist of contour maps at different geographical locations across Canada of four spectral amplitudes (at 0.2, 0.5, 1.0 and 2.0 s) and PGA values to facilitate the implementation of Uniform Hazard Spectrum (UHS) format into design code. The Canadian National Committee on Earthquake Engineering (CANCEE) comprised by about 20 experts on seismic engineering endorsed the 4th national seismic hazard maps in the UHS format developed by the GSC for adoption in the NBCC (2005).

It is important to recall that seismic hazard maps (3rd generation) developed by the GSC for CHBDC (2006) and NBCC (1995) have used accelerogram data corresponding to the ground motions of 10% probability of exceedance in 50 years (475-year return period). But interestingly the GSC, likewise the United States Geological Survey (USGS), used 2% probability of exceedance in 50 years (2475-year return period) for the fourth-generation hazard maps. BSSC 1997 and Adams et al. (1999) studies had pointed that lowering the probability level from 10% in 50-year (widely used in recent codes) provides a better basis for a uniform level of safety across the geographic boundary of applicability of the codes in Canada and the USA and is consistent with the expected target performance of structures. For example, analysis results indicate that buildings designed according to NBCC 1995 (i.e., for a 10% in 50-year design force level) have actually strengths close to the 2% in 50-year design force level in terms of building drifts (Heidebrecht 1999; Biddah 1998). It was also shown that the use of 10% in 50-year hazard as the design basis results in significantly dissimilar risks of structural failure in different regions of Canada.

Features of uniform hazard spectrum

Better accuracy

According to the standardized spectrum, if two sites have the same value for the lone control point (and the same soil condition), then the spectral acceleration coefficients for other periods are supposed to be identical for the two different sites which are highly unlikely. Better accuracy can be achieved if

more site-specific control points can be used as envisaged in the UHS. There seems to be a general consensus of having 3 or 4 minimum control points to capture the correct spectral shape. Humar and Rahgozar (2000) have examined the construction of UHS spectra using eight control points and pointed that too many control points are an unnecessary complication for code application. They recommended using three control points at 0.2, 0.5 and 1.0 s to adequately capture the rational spectral shape. NBCC (2005) used four, whereas AASHTO (2009) used three control points.

Putting near-field and far-field earthquakes in one folder

Short period of design spectra is usually governed by the contribution of near-field accelerogram records (moderate earthquakes) and long period of design spectrum is controlled by far-field records (large earthquakes) (Adams and Atkinson 2003 and Humar and Mahgoub 2003). Getting a common shaped envelope from these two sets of data in the old-style idealized spectral format where a standard shape is to be used for all sites is difficult. This is simply because each site will have different shape of envelopes. However, since UHS uses site-specific data and does not restrict its shape to any prescribed format, it has the flexibility to accommodate this feature by obtaining site-specific spectral ordinates from two sets of motion input (far-field and near-field data). In other words, a UHS comes with the ability to define an envelope of the maximum spectral values produced by two sets of motion inputs and, hence, provides better accuracy and more rational/conservative estimation of design forces.

Approximate spectral coefficients for long periods

There seems to be a lack of sufficient reliable seismological data for long periods (Humar and Mahgoub 2003). Therefore, the shape of the UHS for long period range is approximately defined with the aid of control point of intermediate period. For example, according to NBCC (2005), spectral coefficients for periods larger than 4.0 s are taken as half of spectral coefficient at 2.0 s. As such, these values are considered to be approximate.

Confidence level of hazard maps and its implication

Treatment of uncertainty in hazard analysis is an important area of hazard map development. Depending on the treatment of uncertainties, recent seismic hazard maps are developed for multi-levels of confidence, including high confidence level (median level or 50th percentile) and low



confidence level (median plus one standard deviation level or 84th percentile). Seismic hazard maps with low confidence were developed for codes prior to UHS format application. But with the advent of improved modeling techniques and new earthquake information, maps are produced for both confidence levels in recent years, e.g., fourth-generation seismic hazard maps of Canada (Adams and Atkinson 2003). A study on fourth-generation hazard maps for Canada developed by GSC indicates that the ratio of hazard values of 84th percentile to 50th percentile is substantial, ranging from approximately 1.5–3 (Heidebrecht 1997, 1999). On the other hand, lower probability produces larger seismic coefficients. It is therefore important to note that the choice of combination of probability level and confidence level has a significant implication to the final hazard values and eventually to the design earthquake forces. For example, for NBCC (1995) hazard values are computed at 10% in 50-year probability level with 84th percentile confidence level. Had the hazard maps for NBCC (2005) been developed lowering the probability level to 2% in 50 years without changing the confidence level, then there would have been an obvious increase in the hazard values and, therefore, design forces. Since the confidence level has been changed to the 50th percentile level, there seems to be a compensating effect on the eventual hazard values to be estimated from NBCC (2005) provisions. However, general multiplicative factor cannot be deduced from this combination as the spectral formats (i.e., standardized and UHS) are different between the two versions of the code. Adopting fourth-generation seismic hazard maps in UHS format into CHBDC should be viewed, in that perspective and perceived fear of increased design earthquake force is not a straightforward fallout and needs detailed examinations.

Statistical analysis of seismic data

A total of 389 Canadian cities have been chosen for this study. These cities have been selected from the list of cities of Table A3.1.1 in CHBDC (2006). This table contains names of cities and corresponding seismic data including zonal acceleration ratios A . Cities with zero or missing A values are excluded from this study. The reason of this exclusion is that the denominator in the normalized C_{sm}^* (defined later) becomes zero (hence infinite C_{sm}^*) which leads to ‘ineffective’ statistical data. In recent times, a comprehensive list of seismic data of spectral coefficients $S_a(T)$ for more than 650 Canadian cities corresponding to fourth-generation hazard maps at 2% in 50-year probability level has been published by Adams and Atkinson (2003). The longitude and latitude of the cities are also given in this publication. This information has been utilized to retrieve seismic data of spectral coefficients $S_a(T)$ and PGA at other

probability levels of 5% in 50-year and 10% in 50-year for all 389 cities required for this research. This is accomplished using an online seismic hazard calculator (GSC 2009) developed by Natural Resources Canada. A complete listing of seismic hazard data of the selected 389 cities is saved in the text input file (spectra.in) for the computer program written for this study. A sample of the partial input file (spectra.in) is shown in Fig. 2 for the first city Abbotsford enlisted in Table A3.1.1 in CHBDC (2006).

To manage huge data of 389 cities and carry out associated voluminous numerical analyses, a computer program has been developed for this research. The program is written in Digital Visual FORTRAN (1998) programming language. It consists of a main program (uhs.f) and several subroutines (gsc.f, aashto.f and initial.f). The program does the following tasks:

- Reads all input data for 389 cities from spectra.in file and store them in array format.
- Creates output files echoing input data to make sure that the input data are correctly read by the program.
- Calculates data for spectra construction (C_{sm} vs. Period).

The elastic seismic design forces are calculated based on the elastic seismic response coefficients C_{sm} which in turn are obtained from spectral coefficients ($S_a(T)$) and or ground motion parameters (A and PGA) properly modified by the appropriate site coefficients ($F_a(T)$, $F_v(T)$, S and F_{pga}) and importance factor I .

Where C_{sm} is elastic seismic response coefficient as defined by CHBDC (2006) and AASHTO (2009), A is the zonal acceleration ratio as defined by CHBDC (2006), PGA is the peak ground acceleration coefficient as defined by AASHTO (2009), F_a is the acceleration-based site coefficient as defined by NBCC (2005) and AASHTO (2009), F_v is the velocity-based site coefficient as defined

```

TOTAL NUMBER OF CITIES: 389
*****
SERIAL NUMBER OF CITY: 001
Site Coordinates: 49.1 'N 122.25 'W
ABBOTSFORD
Requested by: ALI AHMED

National Building Code interpolated seismic hazard values
2%/50 years (0.000404 per annum) probability
Sa(0.2) Sa(0.5) Sa(1.0) Sa(2.0) PGA
0.918 0.619 0.310 0.165 0.452 g

Interpolated seismic hazard values at other probabilities
40%/50 years (0.01 per annum)
Sa(0.2) Sa(0.5) Sa(1.0) Sa(2.0) PGA
0.223 0.143 0.074 0.038 0.115 g
10%/50 years (0.0021 per annum)
Sa(0.2) Sa(0.5) Sa(1.0) Sa(2.0) PGA
0.486 0.321 0.159 0.083 0.243 g
5%/50 years (0.001 per annum)
Sa(0.2) Sa(0.5) Sa(1.0) Sa(2.0) PGA
0.661 0.441 0.217 0.115 0.327 g
ACCELERATION RATIO A FROM CHBDC 2006
0.200

```

Fig. 2 Partial input file of “spectra.in” containing typically formatted seismic data for Abbotsford among 389 cities



by NBCC (2005) and AASHTO (2009), S is the site coefficient as defined by CHBDC (2006) and AASHTO (2009) and F_{pga} is the site coefficient for peak ground acceleration as defined by AASHTO (2009).

To have a uniform basis for comparison of design spectra, it is assumed that the average shear wave velocity v_{avg} of the soil under consideration is 760 m/s so that $F_a = F_v = S = F_{\text{pga}} = 1.0$ and $I = 1.0$. The following five spectral shapes are compared and their relevant features are provided in Table 1:

- 2% in 50-year—a spectrum that is drawn using spectral coefficients $S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$ and $S_a(2.0)$ of fourth-generation seismic hazard maps with 2% in 50-year probability according to Section 4.1.8.4 of NBCC (2005).
- 5% in 50-year—a spectrum that is drawn using spectral coefficients $S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$ and $S_a(2.0)$ of fourth-generation seismic hazard maps with 5% in 50-year probability according to Section 4.1.8.4 of NBCC (2005).
- 10% in 50-year—a spectrum that is drawn using spectral coefficients $S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$ and $S_a(2.0)$ of fourth-generation seismic hazard maps with 10% in 50-year probability according to Section 4.1.8.4 of NBCC (2005).
- CHBDC—a spectrum that is drawn using zonal acceleration ratio A of CHBDC (2006) with 10% in 50-year probability according to Section 4.4.7 of CHBDC (2006).
- AASHTO—a spectrum that is drawn using spectral coefficients $S_a(0.2)$ and $S_a(1.0)$ of fourth-generation seismic hazard maps with 5% in 50-year probability according to Section 3.4.1 of AASHTO (2009).

The program further continues with the following operations:

- To track the extent of change with reference to current CHBDC (2006), a normalized elastic seismic coefficient C_{sm}^* is obtained for each spectrum from the Eq. 2.

$$C_{\text{sm}}^*(T) = \frac{C_{\text{sm},\text{sq}}(T)}{C_{\text{sm},\text{CHBDC}}(T)}, \quad (2)$$

where $C_{\text{sm},\text{sq}}(T)$ is the elastic seismic coefficient for a period T obtained from the spectrum in question and $C_{\text{sm},\text{CHBDC}}(T)$ is the elastic seismic coefficient for a period T obtained from the spectrum defined by CHBDC (2006).

- Statistical analyses from the distribution of C_{sm}^* of 389 cities are conducted to examine the trend of magnification/reduction of C_{sm} values corresponding to those of current CHBDC (2006) along the range of period.
- Writes several output files to save the aforementioned numerical results for subsequent analyses and plotting.

Analysis results and discussion

The results derived from running the aforementioned program are presented in two stages: (1) discuss the trend of the results using case examples for sixteen selected cities; (2) discuss the aggregate results based on statistical analyses using all data corresponding to 389 cities.

To have a good understanding of the relative values of elastic seismic coefficients C_{sm} , sixteen cities Montreal, Toronto, Saint John, Halifax, Moncton, Fredericton, Trois-

Table 1 Features of five spectra

Identifier of spectral shapes	Hazard map	Code and spectral shape	Confidence level (percentile)	Probability level	Reference soil and site coefficients
2% in 50-year	4th generation	NBCC (2005) UHS	50th	2% in 50-year	Soil class C NBCC (2005)
5% in 50-year	4th generation	NBCC (2005) UHS	50th	5% in 50-year	$v_{\text{avg}} = 360\text{--}760$ m/s $F_a = 1.0$, $F_v = 1.0$
10% in 50-year	4th generation	NBCC (2005) UHS	50th	10% in 50-year	
CHBDC	CHBDC (2006)	CHBDC (2006) Standardized	84th	10% in 50-year	Soil profile type I CHBDC (2006) $v_{\text{avg}} > 750$ m/s, $S = 1.0$
AASHTO	4th generation	AASHTO (2009) UHS	50th	5% in 50-year	Site class B AASHTO (2009) 762 m/s $< v_{\text{avg}} < 1524$ m/s $F_{\text{pga}} = 1.0$, $F_a = 1.0$, $F_v = 1.0$



Rivieres, Ottawa, Vancouver, Victoria, Alberni, Tofino, Prince Rupert, Kelowna, Kamloops and Inuvik, which represent seismically low to high active areas and also represent eastern and western Canada have been selected for this section of study. Relevant seismic data needed to represent five spectra under consideration of the sixteen cities are provided in Table 2. The values of zonal acceleration ratios A are taken from CHBDC (2006). The spectral coefficients $S_a(T)$ required to illustrate UHS shapes for these cities are obtained from the aforementioned online seismic hazard calculator (GSC 2009) and are also shown in Table 2. It should be noted that for AASHTO designated S_s and S_1 values are obtained from $S_a(0.2)$ and $S_a(1.0)$ values, respectively, corresponding to 5% in 50-year of Table 2.

The elastic seismic coefficients C_{sm} calculated as a function of T using code-specified procedures for sixteen cities are shown in Fig. 3a–p. In these figures, dark blue thick solid line, green dash-dotted line with diamonds mark, black thin solid line, black dashed line and red solid line with circles represent spectra of 2% in 50-year, 5% in 50-year, 10% in 50-year, CHBDC and AASHTO, respectively. The following features are noted:

- A comparison among the first three spectra (2% in 50-year, 5% in 50-year and 10% in 50-year) clearly shows that lowering probability increases values of C_{sm} about 1.5–3 times for spectra 2% in 50-year from that of 10% in 50-year spectra. It should be noted that these hazard maps for three probabilities use the same confidence level (50th percentile).
- Sensitivity of the four spectra (2% in 50-year, 5% in 50-year, 10% in 50-year and AASHTO) is high for short periods as the rate of decay is very high for $0.2 \text{ s} \leq T \leq 0.5 \text{ s}$ and moderate for $0.5 \text{ s} \leq T \leq 1.0 \text{ s}$ in comparison to current CHBDC (2006). For example, slopes of UHS spectra are 2.1 for $0.2 \text{ s} \leq T \leq 0.5 \text{ s}$ whereas corresponding values are about 1.1 for standardized spectrum of CHBDC (2006). This implies that the results of dynamic analysis are more sensitive with reference to period determination for the UHS than current CHBDC in short period range.
- The 5% in 50-year spectrum is the closest one with that of AASHTO. However, the former gives more conservative C_{sm} values for $T < 1.0 \text{ s}$. They share the same plateau for the peak region and the differences of C_{sm} values along the rest of the period axis are insignificant. The similarity is simply because both spectra are constructed on the basis of the same hazard map (fourth-generation map with 5% in 50-year probability) and the differences, though small, are due to the application of different code formats (CHBDC 2006 and AASHTO 2009).

For clarity of discussions, results C_{sm}^* vs. T of 389 cities are calculated numerically and the following observations are made from the tabulated values:

- Current CHBDC is overly conservative as most parts of the four other spectral values are smaller than $C_{sm}^* = 1$. With some exceptions at very short periods, $C_{sm}^* \ll 1.0$. C_{sm} for 10% in 50-year at Montreal even dips down to as low as only 8% of current CHBDC value ($C_{sm}^* = 0.084$ at $T = 4.0 \text{ s}$). The conservatism in current CHBDC is probably because of two reasons: (1) the rate of decay of C_{sm} at intermediate to long period is proportional to $1/T^{2/3} \sim 1/T^{4/3}$ which is quite slower than theoretical estimation ($\propto 1/T \sim 1/T^2$) and (2) higher mode effects have been conservatively included in CHBDC spectrum for long periods.
- Even though hazard maps for both CHBDC (CHBDC 2006) and UHS spectrum 10% in 50-year use the same probability level, C_{sm}^* vs. T plots for 10% in 50-year UHS ordinates of all cities mostly lie below the CHBDC line $C_{sm}^* = 1.0$. The differences are attributed to the difference of confidence levels, i.e., 50th and 84th percentiles used for fourth-generation hazard and CHBDC (2006) maps, respectively. This is consistent with the observations made by Heidebrecht (1997, 1999) that the ratios of fourth-generation hazard values of 84th and 50th percentiles vary in the range of 1.5–3.0. The differences are more pronounced in long period than short periods. The differences also vary significantly from city to city ($C_{sm}^* = 0.84$ to 0.13 , $C_{sm}^* = 0.58$ to 0.08 , $C_{sm}^* = 0.98$ to 0.46 and $C_{sm}^* = 0.67$ to 0.25 , for Toronto, Montreal, Vancouver and Victoria, respectively). This clearly highlights the fact that fourth-generation hazard map with 10% 50-year should not be used for next CHBDC edition.
- For very short period, C_{sm}^* of 2% in 50-year varies from 1.0 to 2.2. That means if the UHS spectrum (2% in 50-year) is to be adopted for next CHBDC edition, there will be significant increase in elastic seismic design force from current CHBDC force for very short period. And, there will be strong argument against this increment as poor performances of bridges are probably not known under past seismic events in Canada to support such change. A correction factor can be applied to bring the design force values close to that of the current CHBDC values for short period range.
- 5% in 50-year is a preferred one among the four options as (1) increase of design seismic force for short period zone is not very high and (2) it is very close to AASHTO values (i.e., NBCC 2005 and AASHTO 2009 formats are very similar). To allay the fear of too low design seismic force for



Table 2 Seismic data for sixteen selected cities

Seismic parameter	Probability of exceedance					
	2% in 50-year	5% in 50-year	10% in 50-year	2% in 50-year	5% in 50-year	10% in 50-year
–	<i>Montreal, Quebec</i>			<i>Toronto, Ontario</i>		
A	–	–	0.200	–	–	0.050
PGA	0.429	0.287	0.200	0.170	0.108	0.072
$S_a(0.2)$	0.687	0.426	0.288	0.262	0.168	0.105
$S_a(0.5)$	0.340	0.201	0.127	0.126	0.077	0.050
$S_a(1.0)$	0.139	0.081	0.051	0.055	0.034	0.022
$S_a(2.0)$	0.048	0.026	0.016	0.016	0.010	0.006
–	<i>Saint John, New Brunswick</i>			<i>Halifax, Nova Scotia</i>		
A	–	–	0.100	–	–	0.050
PGA	0.225	0.132	0.090	0.122	0.080	0.057
$S_a(0.2)$	0.344	0.229	0.159	0.230	0.155	0.108
$S_a(0.5)$	0.181	0.117	0.079	0.130	0.088	0.062
$S_a(1.0)$	0.081	0.051	0.034	0.069	0.045	0.030
$S_a(2.0)$	0.025	0.016	0.011	0.020	0.013	0.009
–	<i>Moncton, New Brunswick</i>			<i>Fredericton, New Brunswick</i>		
A	–	–	0.100	–	–	0.100
PGA	0.214	0.121	0.071	0.267	0.152	0.094
$S_a(0.2)$	0.295	0.186	0.126	0.386	0.245	0.165
$S_a(0.5)$	0.160	0.102	0.070	0.205	0.128	0.086
$S_a(1.0)$	0.069	0.045	0.031	0.086	0.056	0.037
$S_a(2.0)$	0.022	0.014	0.010	0.027	0.018	0.012
–	<i>Trois-Rivieres, Quebec</i>			<i>Ottawa, Ontario</i>		
A	–	–	0.150	–	–	0.200
PGA	0.405	0.266	0.181	0.411	0.274	0.189
$S_a(0.2)$	0.642	0.387	0.256	0.657	0.405	0.268
$S_a(0.5)$	0.311	0.177	0.115	0.317	0.189	0.119
$S_a(1.0)$	0.125	0.073	0.045	0.132	0.079	0.049
$S_a(2.0)$	0.043	0.024	0.015	0.044	0.025	0.016
–	<i>Montreal, Quebec</i>			<i>Toronto, Ontario</i>		
A	–	–	0.200	–	–	0.400
PGA	0.460	0.331	0.245	0.608	0.447	0.336
$S_a(0.2)$	0.927	0.665	0.489	1.217	0.892	0.671
$S_a(0.5)$	0.641	0.454	0.333	0.817	0.595	0.444
$S_a(1.0)$	0.334	0.236	0.173	0.380	0.275	0.205
$S_a(2.0)$	0.173	0.120	0.087	0.185	0.130	0.094
–	<i>Alberni, British Columbia</i>			<i>Tofino, British Columbia</i>		
A	–	–	0.300	–	–	0.300
PGA	0.355	0.257	0.192	0.523	0.332	0.273
$S_a(0.2)$	0.757	0.536	0.395	1.203	0.763	0.628
$S_a(0.5)$	0.559	0.380	0.292	0.937	0.595	0.489
$S_a(1.0)$	0.302	0.208	0.152	0.474	0.301	0.247
$S_a(2.0)$	0.161	0.110	0.079	0.206	0.122	0.097
–	<i>Prince Rupert, British Columbia</i>			<i>Kelowna, British Columbia</i>		
A	–	–	0.150	–	–	0.050
PGA	0.179	0.126	0.094	0.137	0.097	0.072
$S_a(0.2)$	0.377	0.257	0.184	0.276	0.189	0.135
$S_a(0.5)$	0.247	0.169	0.123	0.172	0.119	0.086



Table 2 continued

Seismic parameter	Probability of exceedance					
	2% in 50-year	5% in 50-year	10% in 50-year	2% in 50-year	5% in 50-year	10% in 50-year
$S_a(1.0)$	0.150	0.106	0.078	0.094	0.068	0.051
$S_a(2.0)$	0.086	0.061	0.045	0.056	0.041	0.030
–	<i>Kamloops, British Columbia</i>			<i>Inuvik, Northwest Territories</i>		
A	–	–	0.050	–	–	0.050
PGA	0.138	0.097	0.071	0.062	0.045	0.035
$S_a(0.2)$	0.277	0.188	0.134	0.116	0.076	0.059
$S_a(0.5)$	0.171	0.119	0.089	0.070	0.054	0.043
$S_a(1.0)$	0.105	0.075	0.056	0.041	0.031	0.025
$S_a(2.0)$	0.062	0.044	0.033	0.026	0.020	0.016

intermediate and long periods, a compromising calibration factor should be used.

To track the distribution C_{sm}^* data in the C_{sm}^* vs. T diagram for the four spectra (viz., 2% in 50-year, 5% in 50-year, 10% in 50-year and AASHTO), C_{sm}^* vs. T diagrams are plotted in Fig. 4a–d. From Fig. 4a, it is evident that in the short period range, most of the data lie above the $C_{sm}^* = 1.0$ line. The extents of variation of base shear for most of the cities are in the range of 90–200% and 40–140% for short and long period ranges, respectively. There is a general trend of less magnification with increasing period. The maximum magnification or reduction goes as high as 6 times and as low as 0.4 times, respectively.

From Fig. 4b, it is evident that in the short period range, the majority of the data lie below the $C_{sm}^* = 1.0$ line. The extents of variation of base shear for most of the cities are in the ranges of 60–200% and 30–110% for short and long period ranges, respectively. There is a general trend of less magnification with increasing period. The maximum magnification or reduction attains as high as 4 times and as low as 0.1 time, respectively.

From Fig. 4c, it is evident that most of the data lie below the $C_{sm}^* = 1.0$ line. The extents of variation of base shear for most of the cities are in the range of 40–100% and 20–80% for short and long period ranges, respectively. There is a general trend of less magnification with increasing period. The maximum magnification or reduction achieves as high as 3 times and as low as 0.1 time, respectively.

From Fig. 4d, it is evident that the majority of the data lie below the $C_{sm}^* = 1.0$ line. The extents of variation of base shear for most of the cities are in the range of 50–150% and 20–90% for short and long period ranges, respectively. There is a general trend of less magnification with increasing period. The maximum magnification or reduction attains as high as 5 times and as low as 0.1 time, respectively.

Table 3 shows percentage of data (i.e., cities) that fall within $\pm 10\%$ of current CHBDC (2006) base shear value. As evident, quite a low percentage of data (20–1%) lie in this bandwidth. In other words, for most of the data (80–99%), increase or decrease of base shear values falls outside this range. It suggests that if any one of the four spectra is adopted for CHBDC, with reference to the base shear, a dramatic change will be enforced to current provision. Therefore, none of the four spectra can be adopted in the present shapes for the next CHBDC edition. That issue is addressed in the next chapter.

Conclusions

With the development of fourth-generation seismic hazard maps for Canada and with the adoption of more rational spectral format, UHS in NBCC and in AASHTO guide specifications, the prospect of implementing these into CHBDC is also appearing high. On such backdrop, this paper investigated appropriateness and implications of incorporating four probable spectra using 2% in 50-year, 5% in 50-year and 10% in 50-year new hazard maps in NBCC format and 5% in 50-year map in AASHTO format for 389 cities of Canada and the following findings were summarized:

The statistical analysis for the 10% in 50-year spectrum shows that more than 95% of the cities (i.e., about 370 cities out of 389) will have significant drop of base shear as compared with the current shear level of CHBCD (2006). The extents of reduction of base shear are also quite high: at least 50% reduction for 90% of the 389 cities. There is a general trend of more reduction with increasing period.

Base shears are produced from two spectra of CHBDC (2006) using 50th percentile and 84th percentile showed big differences because of two different confidence levels. The big drop of base shear makes the 10% in



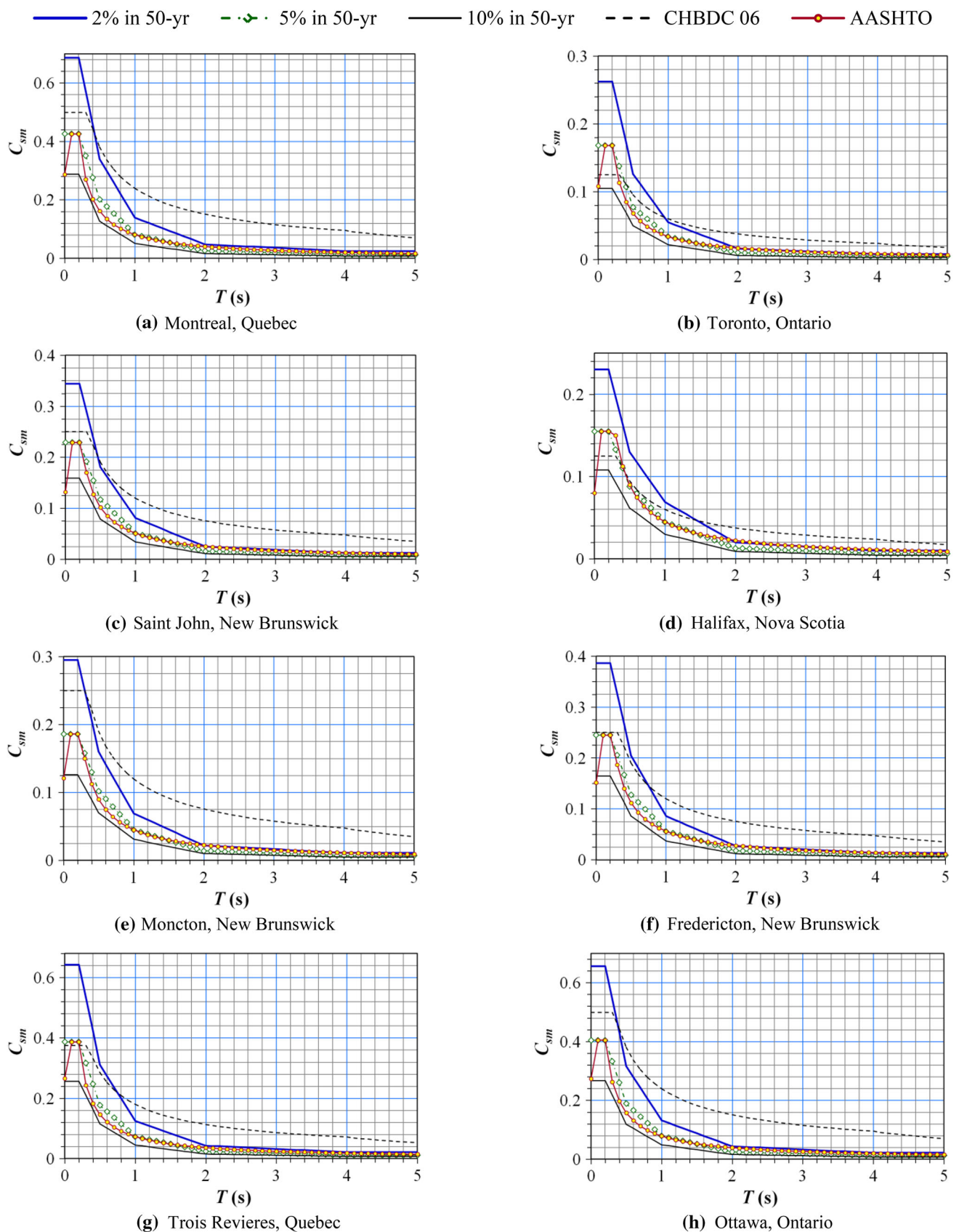


Fig. 3 Comparison of elastic seismic coefficient C_{sm} obtained from five spectra

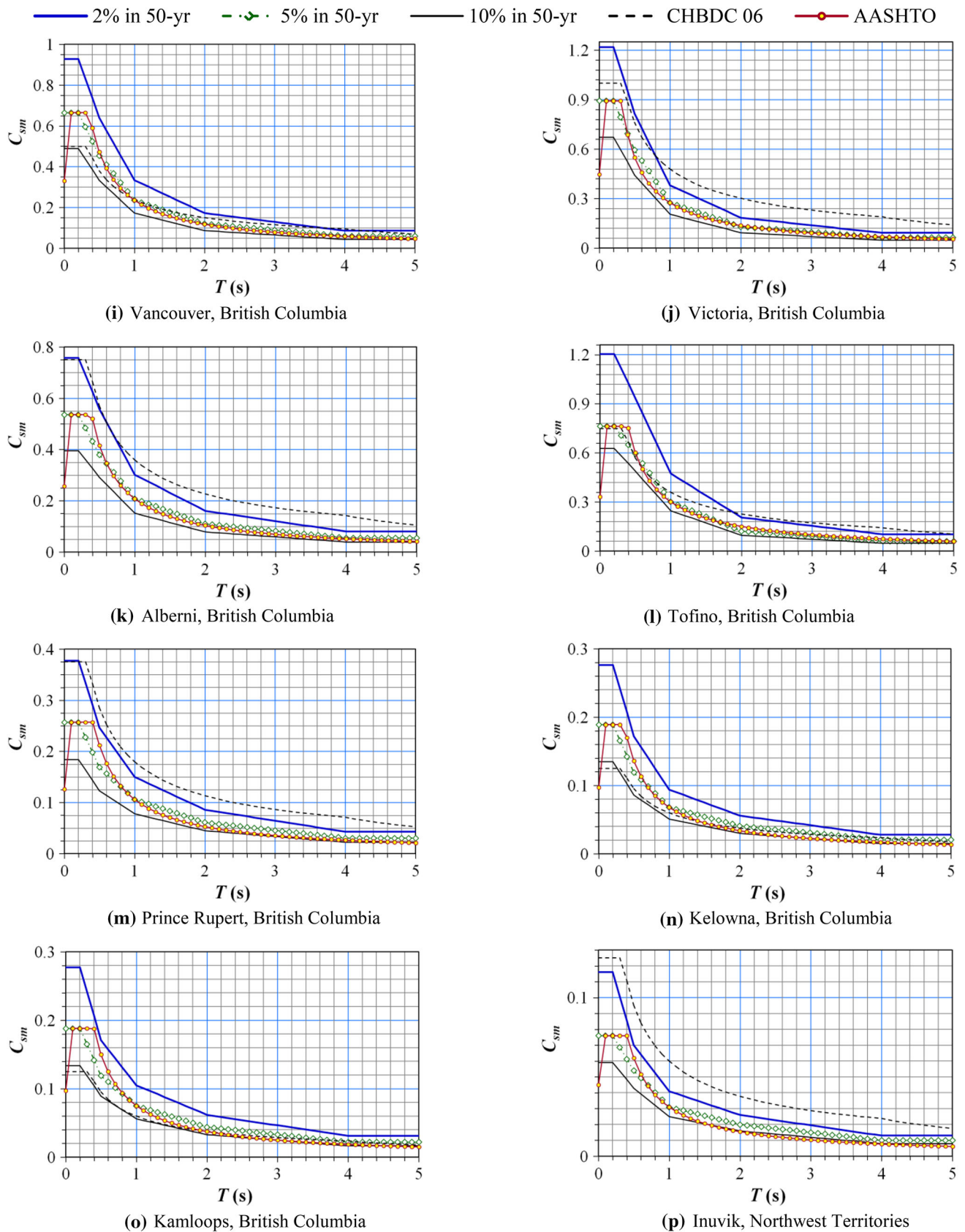


Fig. 3 continued



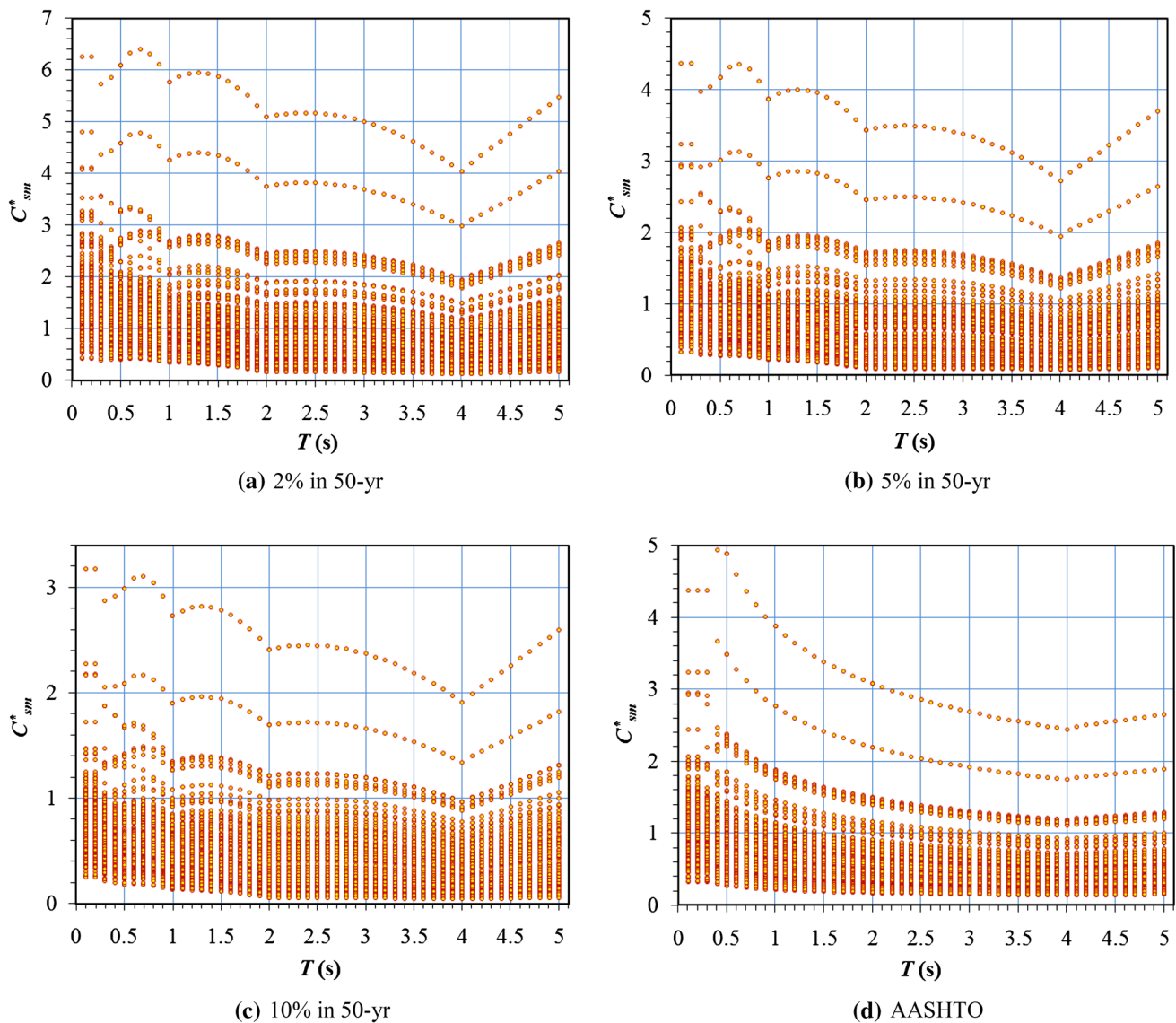


Fig. 4 Distribution of elastic seismic coefficient C_{sm}^* for four spectra of 389 cities

Table 3 Percentage of cities $\pm 10\%$ base shear change from the current CHBDC level

Spectrum	Percentage (%) of data in preferred band width $0.9 \geq C_{sm}^* \leq 1.1$				
	Range 1 0–0.5 s	Range 2 0.5–1.0 s	Range 3 1.0–2.0 s	Range 4 2.0–4.0 s	Range 5 4.0–5.0 s
2% in 50-year	16.3	18.5	11.4	4.8	5.2
5% in 50-year	17.6	10.2	4.8	2	1.9
10% in 50-year	7.9	2.4	1.2	0.9	1.1
AASHTO	18.5	7.5	2.5	1	0.7

50-year spectrum inappropriate for use in the forced based design method (FBD).

The statistical analyses for the 5% in 50-year spectrum show similar trend of 10% in 50-year spectrum, but the extents of amplification happen on a lesser scale. Again,

the drop of base shear is observed for most of the cities. The magnitudes of reduction of base shear are big enough to be concerned. The same general trend of more reduction with increasing periods is noticeable. Therefore, the adoption of this spectrum in its present shape into CHBDC



is not practical. However, the nature of base shear level variation suggests that this spectrum can be ‘modified’ to bring the base shear level in an acceptable range.

The statistical analyses for the 2% in 50-year spectrum reveal that for shorter period range, there will be an increase but for longer period range, there will be a significant decrease of base shear from that of the current CHBDC provision. Similar to the 5% in 50-year spectrum, the nature of base shear level variation for 2% in 50-year suggests that this spectrum can also be ‘modified’ to bring the base shear level in an acceptable range. However, the degree of modification will not be as high as of 5% in 50-year spectrum.

Since AASHTO uses fourth-generation seismic hazard maps with 5% probability of exceedance in 50-year, the comments made for the statistical analyses of 5% in 50-year spectrum work well for AASHTO spectrum. Again, the nature of base shear level variation suggests that this spectrum needs to be ‘modified’ for CHBDC incorporation to bring the base shear level in an acceptable range. However, a different approach is needed for modification.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- AASHTO (2009) AASHTO Guide Specifications for LRFD Seismic Bridge Design. American Association of State Highway and Transportation Officials, Washington, USA
- Adams J, Atkinson G (2003) “Development of seismic hazard maps for the proposed 2005 edition of the National Building Code of Canada”. *Can J Civ Eng* 30:255–271
- Adams J, Halchuk S (2003) “Fourth generation seismic hazard maps of Canada: values for over 650 Canadian localities intended for the 2005 National Building Code of Canada,” Geological Survey of Canada Open File 4459, pp 1–155. <http://earthquakescanada.nrcan.gc.ca/hazard-alea/OF4459/index-eng.php>
- Adams J, Weichert D, Halchuk S (1999) Lowering the Probability Level—Fourth Generations Seismic Hazard Results for Canada at 2% in 50 Year Probability Level. In: Proceedings of the 8th Canadian Conference on Earthquake Engineering, Canadian Association for Earthquake Engineering, Vancouver, Canada, pp 83–88
- Biddah A (1998) Evaluation of the Seismic Level of Protection of Steel Moment Resisting Frame Building Structures, Ph.D. Thesis, McMaster University, Hamilton, ON, Canada
- Biot MA (1933) Theory of elastic systems vibrating under transient impulse with an application to earthquake-proof buildings. *Proc Natl Acad Sci* 19(2):262–268
- Biot MA (1934) Theory of vibration of buildings during earthquakes. *Zeitschrift für Angewandte Mathematik und Mechanik* 14(4):213–223
- BSSC (1997) Building Seismic Safety Council, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Part 1: Provisions (FEMA 302) and Part 2: Commentary (FEMA 303), Washington D.C., USA
- CHBDC (2006) Canadian highway bridge design code. Canadian Standard Association, Mississauga
- Digital Visual FORTRAN, Version 6.0 (1998) Standard Editions, Digital Equipment Corporation, Maynard, Massachusetts, USA
- Geological Survey of Canada (2009) Interpolate 2005 National Building Code of Canada seismic hazard map values for your site, Natural Resources, 11 December. <http://earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/index-eng.php>
- Hasan R, Tharmabala B, Ahmed A (2010) “Evaluation of elastic seismic coefficient in the context of new seismic hazard map for Canada”. In: Proceedings of the 8th International Conference on Short and Medium Span Bridges, Canadian Society for Civil Engineering, Niagara Falls, pp 103–1–103–10
- Heidebrecht AC (1997) Seismic level of protection for building structures. *Can J Civ Eng* 24:20–33
- Heidebrecht AC (1999) “Implications of new Canadian uniform hazard spectra for seismic design and the seismic level of protection of building structures”. In: Proceedings of the 8th Canadian Conference on Earthquake Engineering, Canadian Association for Earthquake Engineering, Vancouver, Canada, pp 213–218
- Housner GW (1941) “An investigation of the effects of earthquakes on buildings,” Ph.D. Thesis, California Institute of Technology, Pasadena, California, USA
- Housner GW (1947) Characteristics of strong motion earthquakes. *Bull Seismic Soc Am* 37(1):19–31
- Humar JL, Mahgoub MA (2003) Determination of seismic design forces by equivalent static load method. *Can J Civ Eng* 30:287–307
- Humar JL, Rahgozar MA (2000) Application of uniform hazard spectra in seismic design of multistory buildings. *Can J Civ Eng* 27:563–580
- NBCC (1995), National Building Code of Canada, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, Canada
- NBCC (2005) National Building Code of Canada, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, Canada

